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**The Compact Muon Solenoid (CMS)
Electromagnetic Calorimeter**

B. Ille

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The Compact Muon Solenoid (CMS) Electromagnetic Calorimeter

B. Ille¹

*Institut de Physique Nucléaire de Lyon, IN2P3-CNRS/Université Lyon-I, F-69622
Villeurbanne, France*

Abstract

The Electromagnetic Calorimeter of the CMS detector for the CERN Large Hadron Collider (LHC) is designed to allow the detection of a standard model Higgs boson of mass below 150 GeV. An overview is given of this homogeneous calorimeter made of almost 80000 Lead Tungstate ($PbWO_4$) $26 X_0$ long crystals. This includes a description of the engineering design and a review of the different components of the calorimeter. The most recent results obtained in particle beams with realistic crystal prototypes are also presented.

¹ On behalf of the CMS collaboration

1 Introduction

The Compact Muon Solenoid (CMS) detector is a general purpose detector designed for use in the Large Hadron Collider (LHC) at CERN. Its description and design specifications necessary to exploit the challenging experimental conditions at the LHC have been presented in this conference [1]. The electromagnetic calorimeter (ECAL) will play a crucial role in the study of the Higgs sector, in particular the mass range below $\approx 150 \text{ GeV}/c^2$ where the natural width of the Higgs boson is narrow (a few MeV) and it is expected to be observed through its decay into two photons. This is why the CMS collaboration is building a very high performance homogenous ECAL. For example, if we parametrize the energy resolution σ in the usual way :

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (1)$$

then typically, for the barrel, we predict a constant term $c = 0.55\%$, a stochastic term $a = 2.7\%$ (if E in GeV) and a noise term as low as 155 MeV in the low-luminosity regime of the LHC.

This note is a short status report describing the different components of the ECAL and some of the most recent performances obtained with prototypes in particle beams.

2 The calorimeter design

2.1 Lead-tungstate (PbWO_4) as a homogenous medium

Because of the design of CMS, the ECAL, situated between the central tracker and the hadronic calorimeter, has to be very compact and resistant to the hostile environment of the LHC (ionizing dose rates up to 0.3 Gy/h in the barrel, and up to 15 Gy/h in the endcaps with a neutron fluence ranging from $\approx 2 \times 10^{13}$ to a few 10^{14} n/cm^2 near $\eta = 3$). Table 1 summarizes the characteristics of different inorganic scintillating materials investigated for use in high-energy particle experiments. It is clear that PbWO_4 is the best candidate from the point of view of compactness : it has a small radiation length ($X_0 = 0.89 \text{ cm}$) and a small Molière radius (2.2 cm) so that a very compact and highly granular calorimeter can be constructed. Moreover it has a fast scintillation emission (more than 95% of the light emitted in 100 ns), which is compatible with the 25 ns beam crossing time of the LHC. It has however two main drawbacks : a poor light output which in addition is subject to a temperature dependence of about 2% per degree Celsius [2]. As a consequence, photodetectors having an internal gain have to be used and the whole detector has to be stabilised in temperature. This, together with the presence of a 4 Tesla magnetic field, puts some constraints on the detector construction.

	Crystals					Noble Liquids				
	NaI(Tl)	BGO	CSI	BaF ₂	CeF ₃	PbWO ₄	LiXe	LiKr	LiAr	
ρ [g/cm ³]	3.67	7.13	4.51	4.88	6.16	8.28	3.52			
X _d [cm]	2.59	1.12	1.85	2.06	1.68	0.89	2.8	4.6	14.2	
R _M [cm]	4.80	2.33	3.50	3.39	2.63	2.19	4.1	4.8	10.1	
τ [ns]	230	60/300	16	0.9,630	8,25	5,15,100	3,25			
n	1.85	2.15	1.80	1.49	1.62	2.30	1.6	1.4		
$\lambda_{\max}$ [nm]	410	480	315	210,310	300,340	440	170			
[%/°C]	~0	-1.6	-0.6	-2, 0	0.14	-2.0	-0.4			
LY[NaI]=100	100	18	20	20,4	8	1.3	~100			
Application	CrystBall	L3	CLEOII	L*, GEM	L3P	CMS	L*			
Accelerator	SPEAR	LEP	CESR	SSC	(LHC)	LHC	SSC			
Readout	PMT	SIPd	SIPd	V4T	VPD	APD/VPT	SIPD	SIPD		

Table 1: Inorganic scintillators

Fig. 1. Overall isometric view of the CMS Electromagnetic Calorimeter.

2.2 The mechanical structure

Figure 1 is an isometric view of the electromagnetic calorimeter, showing the arrangement of the barrel and the two endcaps. The calorimeter comprises almost 80000 lead tungstate crystals, organized in "submodules", "modules" and "supermodules" for the barrel and "supercrystals" for the endcaps [3].

The ECAL barrel has an inner radius of 124 cm and covers a pseudorapidity interval $-1.48 \leq \eta \leq 1.48$. A granularity of $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ is achieved with 23 cm long ($26X_0$) crystals having a front face area $\approx 22 \times 22 \text{ mm}^2$, pointing to the vertex except for an angular tilt of $\approx 3^\circ$ both in η and ϕ . The mechanical structure is made of thin fibreglass alveolae carrying a reflective aluminium inner coating. The gap between crystals is $< 500 \mu\text{m}$. The smallest mechanical cell is a submodule of 5×2 crystals. Depending on η , forty or fifty submodules are assembled into modules. A supermodule consists of four modules (1700 crystals, see figure 2) held by a U-shaped spine. There are in total 36 supermodules (61200 crystals) in the barrel, each of which will be precalibrated in beam before installation.

The two endcaps each contain two detectors: a preshower device followed by a lead tungstate calorimeter. The preshower consists of 1.8 mm silicon-strip detectors after $2 \times X_0 + 1 \times X_0$ lead absorber (strip length $\approx 60 \text{ mm}$, $300 \mu\text{m}$ thick, detector inner radius of 45 cm with an outer radius of 125 cm, total Si active area $\approx 16.4 \text{ m}^2$). It will measure the shower position with a precision $< 400 \mu\text{m}$ and will improve the neutral pion rejection in the forward region ($1.65 < \eta < 2.6$). Each crystal endcap is made up from 4 identical Dee-shaped structures, each being made of "supercrystals" of 5×5 22 cm long identical crystals in alveolar structure made of the same material as in the barrel. The lateral dimensions of those crystals are $28.5 \times 28.5 \text{ mm}^2$ for the front face (which is 3170 mm away from the detector centre) and $30 \times 30 \text{ mm}^2$ for the rear face. As for the barrel, the crystal axes are off-pointing from the vertex by $\approx 3^\circ$. The total number of crystals is nearly 8000 per endcap.

The front-end readout electronics is situated on the detector, just behind the crystals in the case of the barrel (see figure 2). Two active cooling systems

Fig. 2. View in η of the ECAL module 2.

will maintain a stable temperature, one for extracting the heat generated by the electronics (≈ 15 Watts per submodule) and the other one for keeping the crystals and photodetectors (APDs) within a tight temperature tolerance ($\approx \pm 0.1^\circ \text{C}$) [3].

2.3 *Crystal Development and Construction*

The CMS collaboration has conducted a considerable R & D program jointly with manufacturers in Russia (Bogorodisk) and China (Shanghai Institute of Ceramics, Beijing Glass Research Institute) to develop large PbWO_4 crystals of a quality suitable for the ECAL. In particular the radiation hardness of crystals, which is one of the major issues of the ECAL, has been improved considerably : light collection losses of only about 2% only have been achieved for a typical LHC dose rate (high luminosity). In summer 1999 more than 1000 preproduction crystals from Russia (Bogorodisk) were delivered and tested. There was, in the calorimetry session of this conference, a detailed presentation [2] describing the huge progress made in the fabrication and processing of the crystals as well as the automated control systems working in the two Regional Centers (CERN and ENEA Laboratory in Roma) in charge of these tasks. The efficiency of these improvements ~~is~~ will be illustrated below with the performance of small prototypes in particle beams.

2.4 *Calibration and Monitoring*

To achieve the required resolution on the measured energy, it is very important to perform a precise precalibration of each crystal by exposing the supermodules and Dees to high-energy electron beams. A calibration of each crystal at two energies is foreseen. A sophisticated laser system injects short 440 nm light pulses (close to the wavelength of the PbWO_4 scintillation signal) into each individual crystal at the front face via a two-level distribution system of quartz fibres [4]. Two independent PIN photodiodes, each associated to a DMILL analog electronics chain, monitor the stability of the laser source. The whole system is able to monitor precisely the response of the struck crystal. For example, a stability better than 0.1 % has been achieved during two weeks of data taking in 1999. In the CMS detector, during LHC running, the

Fig. 3. Readout capsules, with APDs.

same monitoring system will track small short-term changes of transparency of each crystal induced by radiation (radiation affects only the light transmission of the crystal), allowing a precise monitoring correction of the calibration constants [5].

In situ, an absolute calibration using physics events such as $Z \rightarrow e^+e^-$ or $W \rightarrow e\nu$ will be performed every one or five weeks (depending on luminosity). Combining these methods, a calibration at the level of $\approx 0.3\%$ will be achieved within a month at low luminosity.

3 Crystal Readout

3.1 Photodetectors

The photodetectors must operate in the 4 Tesla CMS solenoidal magnetic field and in a hostile, η -dependant radiation environment. Moreover they must have some internal gain, because of the low light yield produced by $PbWO_4$.

In the barrel, Avalanche Photodiodes (APDs) are used because of their insensitivity to magnetic field and because they can operate in the barrel neutron flux. After an extensive R & D effort pursued with two manufacturers (EG&G and Hamamatsu Photonics Company) by CMS ECAL institutes, crucial APD parameters like capacitance, leakage current, excess noise factor, quantum efficiency, sensitivity to neutron fluence, gain sensitivity to bias voltage, effective thickness, and break-down voltage were optimized. In summer 1998, the Hamamatsu Company was selected, mainly because of the reliability of their devices. A description of the barrel APDs was covered in this session by a dedicated talk [6]. The crystal readout is made via a "capsule" (shown in figure 3) glued to the rear face of each crystal by radiation-resistant optical glue ($n = 1.6$, Histomount).

Each capsule comprises two 25 mm^2 APDs, connected in parallel to the front-end electronics by mean of a short (7 to 17 cm, depending on η) shielded kapton. In addition, a temperature sensor mounted on 10 % of the capsules

monitors the temperature stability of each submodule. The operating gain value of the APDs is 50. Table 2 summarizes the main parameters of the barrel photodetectors.

Main Characteristics	APD	VPT
Active Area	$2 \times 25\text{mm}^2$	$\approx 300\text{mm}^2$
Quantum efficiency at 420 nm	70%	18%
Capacitance	$2 \times 75 \text{ pC}$	a few pC
Operating gain M	50	7-8 (4 T)
Excess noise factor F	≈ 2	2.5-3
I_{leakage} at M = 50	a few nA	–
I_{leakage} at $2 \times 10^{13} \text{ n/cm}^2$	$\approx 2-3 \mu\text{A}$	–
$\frac{1}{M} \frac{dM}{dV}$ at operating M	3.3%	< 0.1% per V
$\frac{1}{M} \frac{dM}{dT}$ at operating M	- 2.2%	< 1% per $^{\circ}\text{C}$

Table 2: CMS ECAL photodetector characteristics.

The radiation situation in the endcaps is much worse than in the barrel. The neutron fluence and the ionization dose increase rapidly and Si APDs, sensitive to neutron-induced bulk damage, are unsuitable. Vacuum phototriodes (VPTs) are used. Presently several manufacturers (Electron Tubes Ltd., RIE St Petersburg, Hamamatsu Photonics) are optimizing VPT parameters in collaboration with CMS ECAL institutes. A gain of about 7-8 can be achieved in the 4 T axial magnetic field of CMS. Table 2 summarizes the main parameters of typical 1-inch VPTs and allows to compare the advantages and drawbacks of the two types of photodetectors used in ECAL.

3.2 Front-end readout electronics

The readout and trigger electronics were covered in more detail by a dedicated talk in the electronics session at this conference [7]. The choice of CMS was to digitize the scintillation signal on the detector, sending the digitized data to the upper-level by fast optical links (one link per channel). That means the collaboration has to develop a complete so called "light-to-light" chain in radiation resistant, highly integrated technologies. Figure 4 shows a functional diagram of one readout channel, together with the first 5-channel radiation-hard board, the position of which vis-à-vis a typical module is presented in figure 2.

Fig. 4. Functional diagram of the frontend crystal readout with prototype of a 5-channel board.

As shown on the diagram, the scintillation light is converted to a current by the APDs or VPTs, then converted to voltage and amplified (peaking time ≈ 40 ns, four gains) in the first chip ("Floating Point Preamplifier", developed both in Harris UHF1x Complementary Bipolar and DMILL BiCMOS technologies) before being digitized at 40 MHz by an AD9042 12-bit ADC (third chip of the board) from Analog Devices. Then the digital values are serialized and transmitted to the counting room, some 80 m away, on low-power 0.8 Gbits/s fiber-optic links which are being developed in CHFET Complementary GaAs technology (Honeywell). Apart from the preamplifier gain and shaping, matched to the photodetector characteristics (= operating gain and capacitance) and the dynamic range to be covered, the APD and VPT readout chains are identical. A full radiation-hard front-end electronics chain will be operational beginning 2000.

4 Testbeam results

In 1999, realistic (but small) prototypes with almost final mechanical structures and more or less final front-end electronics were tested in high-energy particle beams at CERN. Good performance was obtained, and is summarized in the following sections.

4.1 Testbeam results for endcap modules

Two series of tests have been performed in summer 1999. The first one with a bare "supercrystal" (5×5) matrix was equipped with 1 inch VPTs from three different manufacturers. The crystals were not uniformized and were stabilized at 18°C . No magnetic field was applied. The results concerning the energy resolution on different sets of 3×3 submatrices can be summarized as

Fig. 5. Reconstructed energies for the combined preshower and endcap prototype.

follows [8] :

$$\frac{\sigma}{E} = \frac{4.1\%}{\sqrt{E}} \oplus 0.25\% \oplus \frac{\text{noise}}{E} \quad (2)$$

where the average measured noise was 390 MeV. A typical resolution of 0.51% at 180 GeV was achieved.

In the second test, a $3X_0$ preshower prototype was placed in front of the bare "supercrystal". Figure 5 illustrates both the degradation in the reconstructed energy due to the presence of $3X_0$ in front of the crystals (no preshower correction, in the peak at the left) and the improvement of the energy resolution when the preshower correction is included (peak at the right). An energy resolution of 0.6% at 180 GeV was achieved. All these results are very well-reproduced by Monte Carlo simulation.

4.2 Testbeam results for barrel matrix

In August 1999, a 30-crystal matrix (three submodules of 10 crystals equipped with APD readout capsules) was exposed to high-energy electrons. The crystals were carefully uniformized by depolishing one lateral face and the whole setup was stabilized at 18°C . The APD characteristics were as shown in table 2 : the total capacitance of the readout capsules, including the kapton liaisons, was typically 160-170 pC and the leakage current at gain ≈ 50 was a few nA. The electronic noise of each channel measured under these conditions was $10500 e^-$, which corresponds to ≈ 36 MeV per channel with a small correlated contribution of ≈ 8 MeV. Figure 6 shows an example of the reconstructed energy spectrum at 280 GeV (sum of 9 crystals). No direct detection in the APDs of the shower tail can be seen.

In the same way as for the endcap, the energy resolution measured with different 3×3 barrel submatrices can be summarized by (average value of each

Fig. 6. Energy spectrum at 280 GeV for a 3×3 barrel submatrix around crystal 2070.

Fig. 7. Distribution of stochastic, constant and noise resolution terms for different submatrices.

term, the distributions of which are shown in figure 7) :

$$\frac{\sigma}{E} = \frac{2.6\%}{\sqrt{E}} \oplus 0.4\% \oplus \frac{150\text{MeV}}{E} \quad (3)$$

Here the good value of the stochastic term is mainly due to the fact that we used twin-APD capsules (doubling the active area, hence the photostatistics, which is nearly 5 photoelectrons/MeV) and that the APD excess noise factor is low ($F \approx 2$). The excellent value of the constant term results of course from the quality of the crystal, but also from the quality of the processing (uniformization) and of the inner coating of the alveolae.

5 Conclusion

After many years of R&D, the CMS ECAL community is now in a position to build a calorimeter that can meet the LHC requirements. Testbeam results show that the nominal specifications have been met. The CMS ECAL is now in the preproduction phase with the construction of the first module of 400 channels. Mass production of crystals and mechanical structure has started and mass production of APDs will begin early in 2000. The infrastructure and tooling of the regional centers are ready so that the first barrel supermodule construction can start in spring 2000. Still some more work is needed on the preparation of the production of radiation-hard readout components. A pre-production of the complete electronics chain will occur in 2000. In addition the construction, the ECAL community will now concentrate its efforts on the monitoring and the calibration of the detector.

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References

- [1] J-L. Faure "The CMS detector", These proceedings, October 1999.
- [2] P.Lecoq "First results of lead tungstate crystal production for the CMS calorimeter", These proceedings, October 1999.
- [3] CMS Collaboration "The electromagnetic calorimeter project : Technical Design Report", CERN/LHCC 97-33, December 1997.
- [4] L.Zhang, R.Y.Zhu, D. Liu "Monitoring Lasers for $PbWO_4$ ECAL", CMS IN 1999/014
- [5] J.Bourotte et al "The ECAL Precalibration in H4: User Requirements Document", CMS NOTE-1999/024
- [6] K.Deiters "Properties of the Avalanche Photodiodes for the CMS Electromagnetic Calorimeter", These Proceedings, October 1999.
- [7] B.Lofstedt "The readout system of the CMS electromagnetic calorimeter", These proceedings, October 1999
- [8] D. Newbold, E.Tournefier "EE Beam Tests '99" and "Preshower beam test 1999 Results" CMS internal reports, 1999